High Mobility Si/SiGe Strained Channel MOS Transistors with HfO_2/TiN Gate Stack

S. Datta, G. Dewey, M. Doczy,
B. Doyle, B. Jin, J. Kavalieros,
R. Kotlyar, M. Metz, N. Zelick and
Robert Chau

Components Research
Intel Corporation

Contact Information: Robert.S.Chau@intel.com

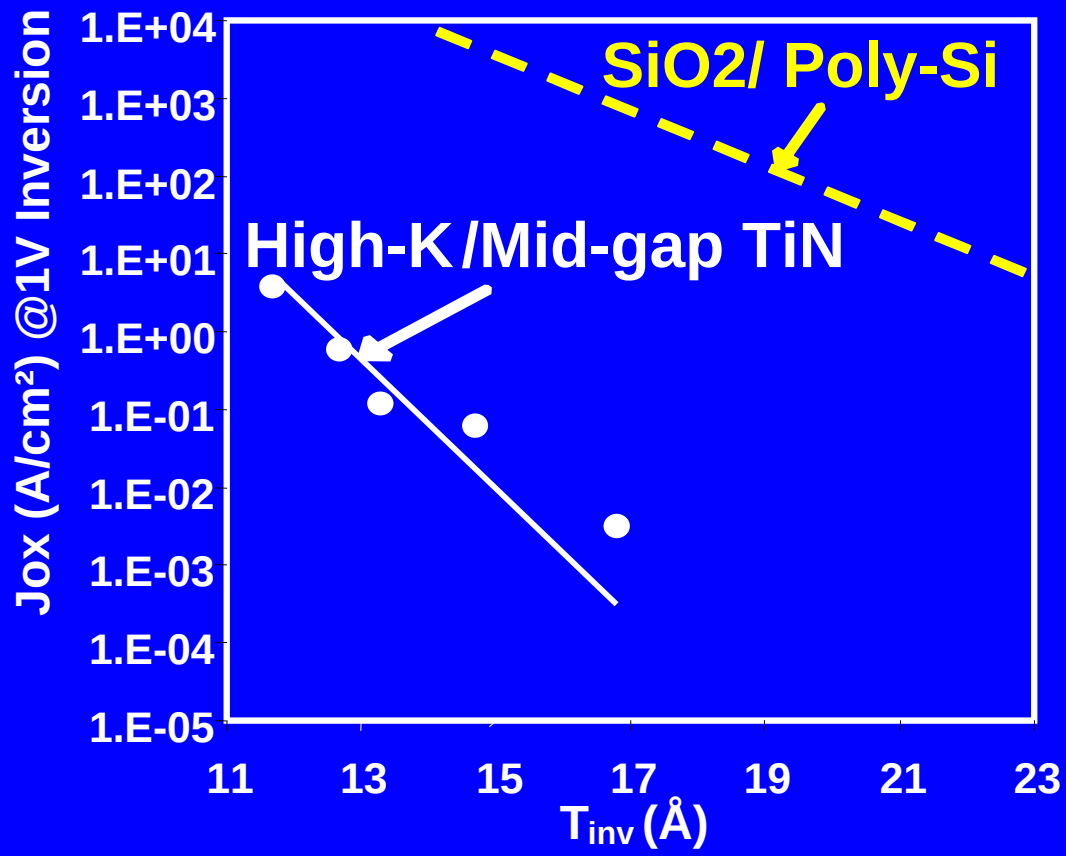
Outline

- Introduction
- High-K / Poly-Si Mobility
- High-K / Mid-Gap TiN Metal Gate Mobility
- High-K / Mid-Gap TiN Metal Gate Stack with Strained Si Channel
- High-K Mobility with n+ and p+ Work-Function Metal Gate Electrodes

Introduction

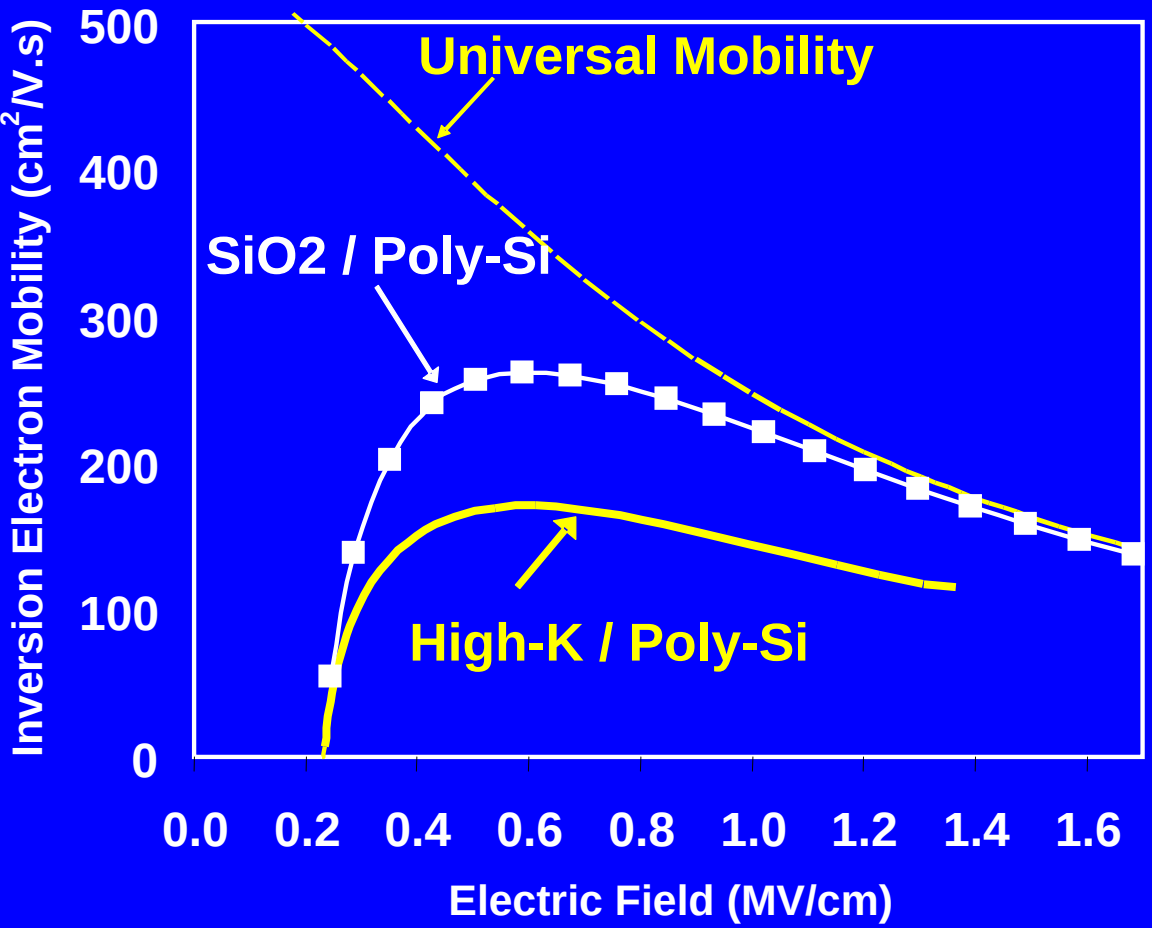
- **Objectives**
  - **Understand the fundamental High-K Mobility Degradation Problem**
  - **Demonstrate High-K mobility enhancement can be achieved by either Metal Gate or Strained Si**
  - **Demonstrate High-K mobility can be further enhanced by combining Metal Gate and Strained Si**

Gate Stack Scaling



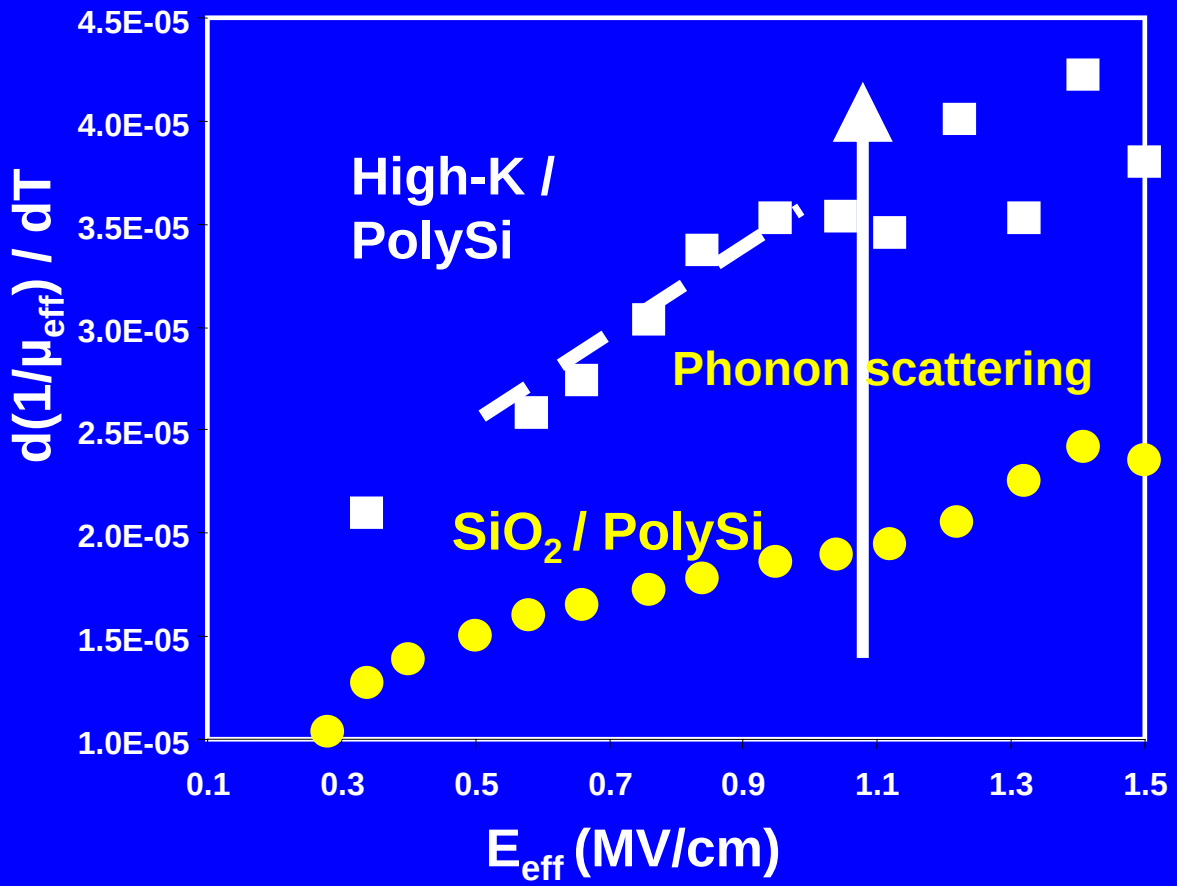
- Gate leakage increases with SiO2 scaling -> running out of atoms
- Alternate Gate Stack needed to scale EOT and maintain low gate leakage

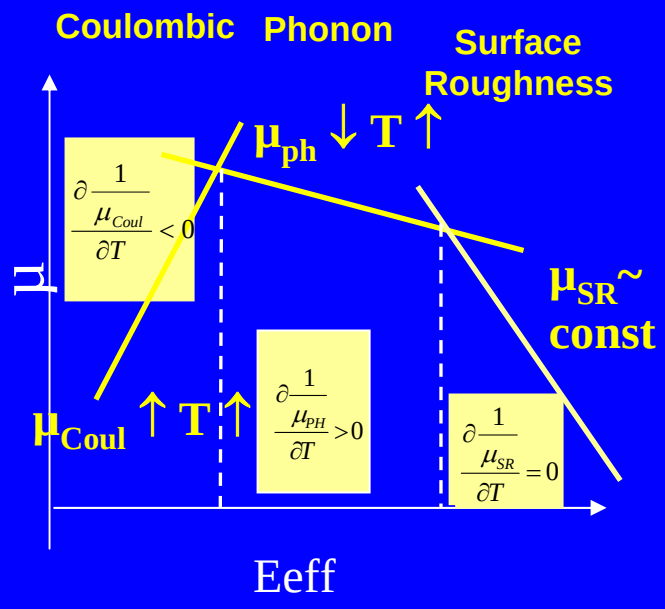
High-K / Poly-Si Electron Mobility



- Electron Mobility is significantly degraded with High-K + Poly-Si gate electrode

Experimental Evidence of Phonon Scattering in High-K

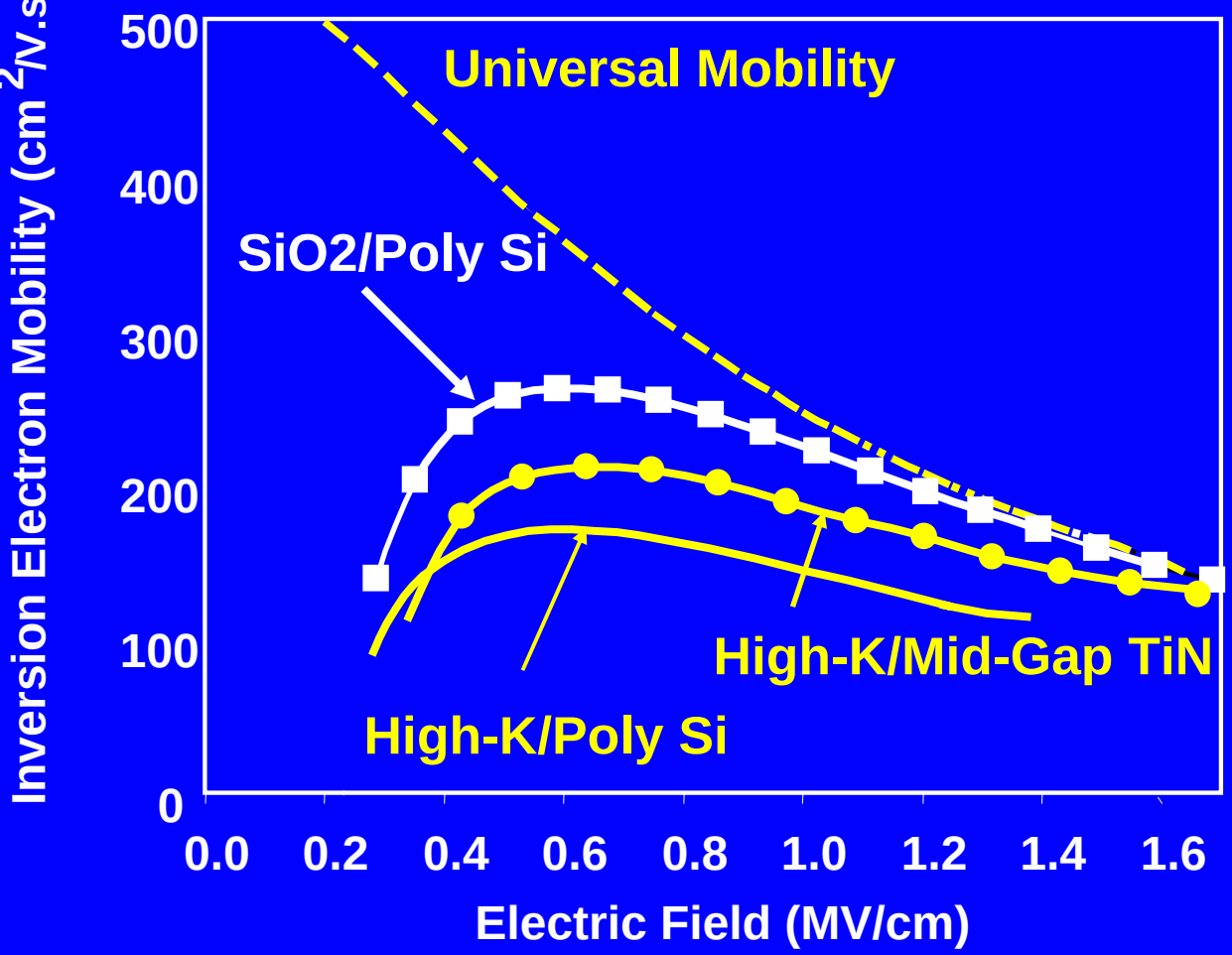


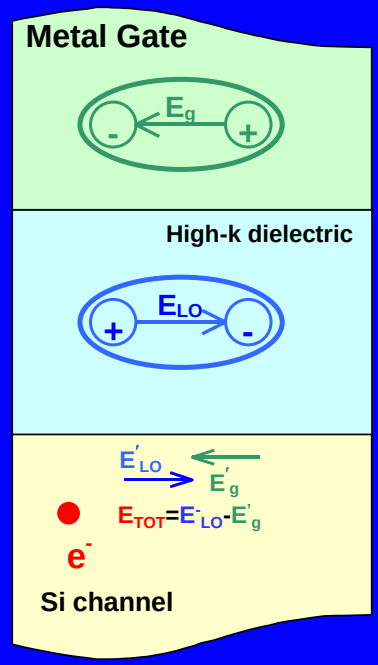


$$\frac{\partial \frac{1}{\mu_{Coul}}}{\partial T} < 0 \qquad \frac{\partial \frac{1}{\mu_{PH}}}{\partial T} > 0 \qquad \frac{\partial \frac{1}{\mu_{SR}}}{\partial T} = 0$$

$$\frac{1}{\mu_{eff}} = \frac{1}{\mu_{Coul}} + \frac{1}{\mu_{ph}} + \frac{1}{\mu_{SR}}$$

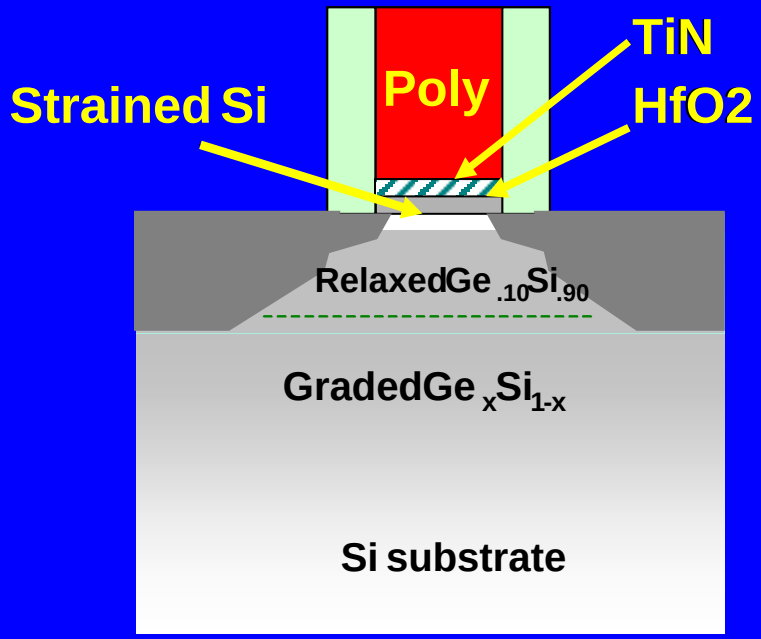
High-K Mobility Enhancement with Mid-Gap TiN

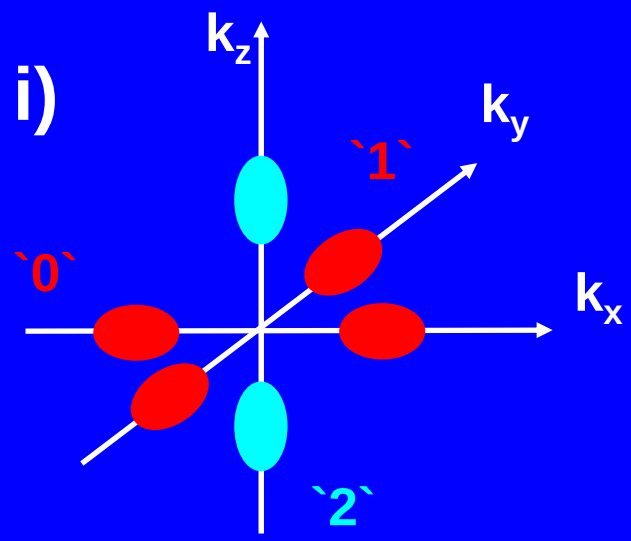


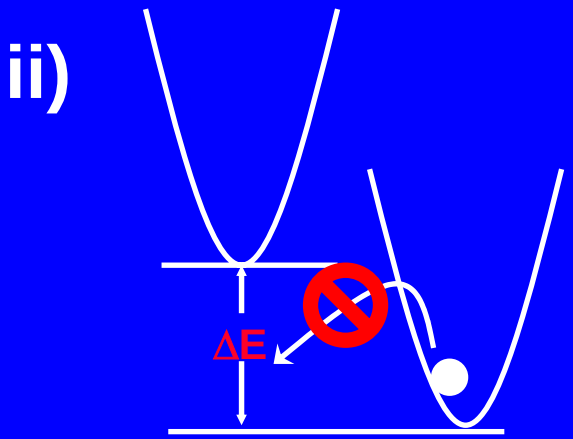


- Electron mobility is significantly improved with Mid-Gap TiN Metal Gate

Strained Si Channel + Hi-K / Mid-Gap TiN Metal Gate Stack

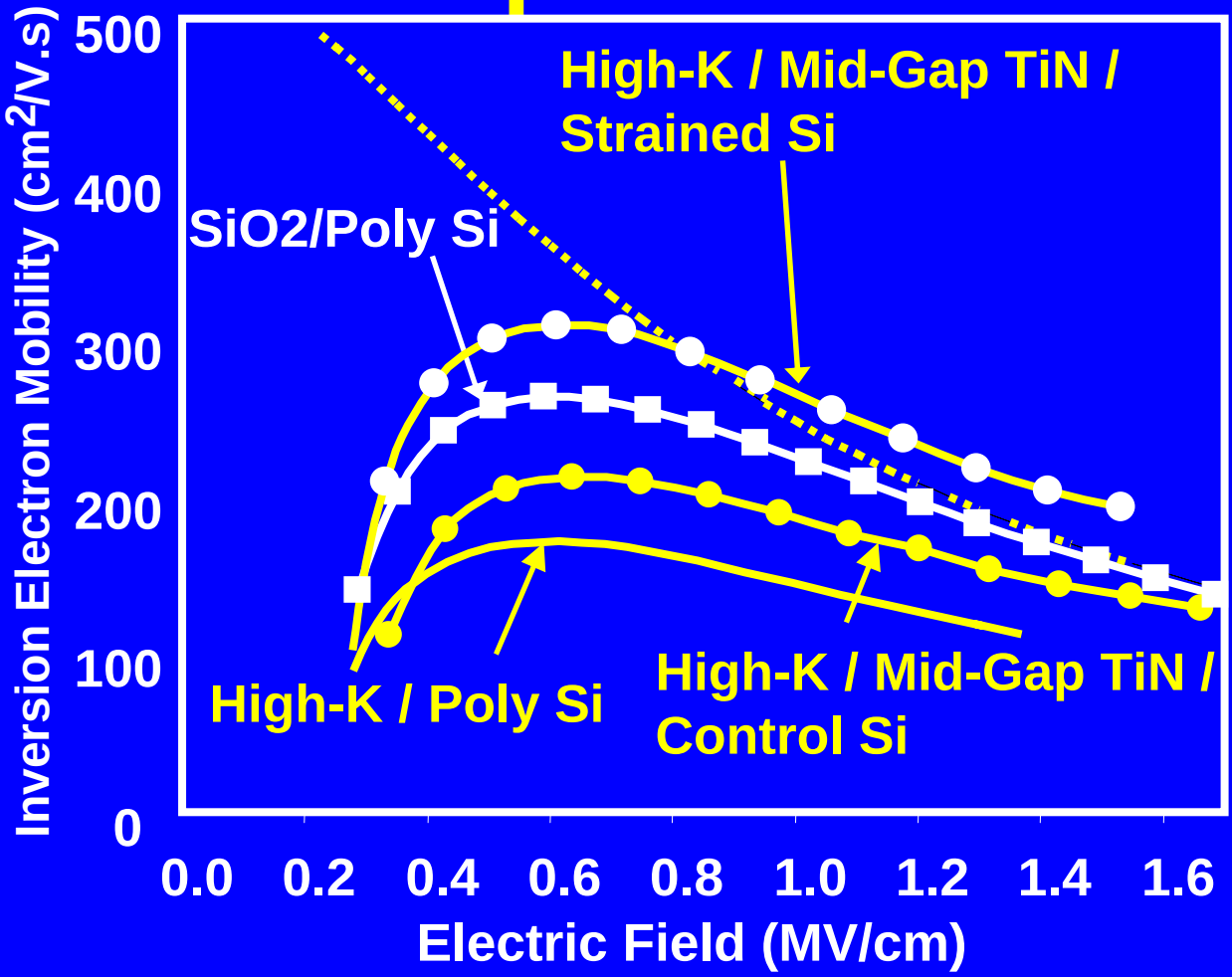






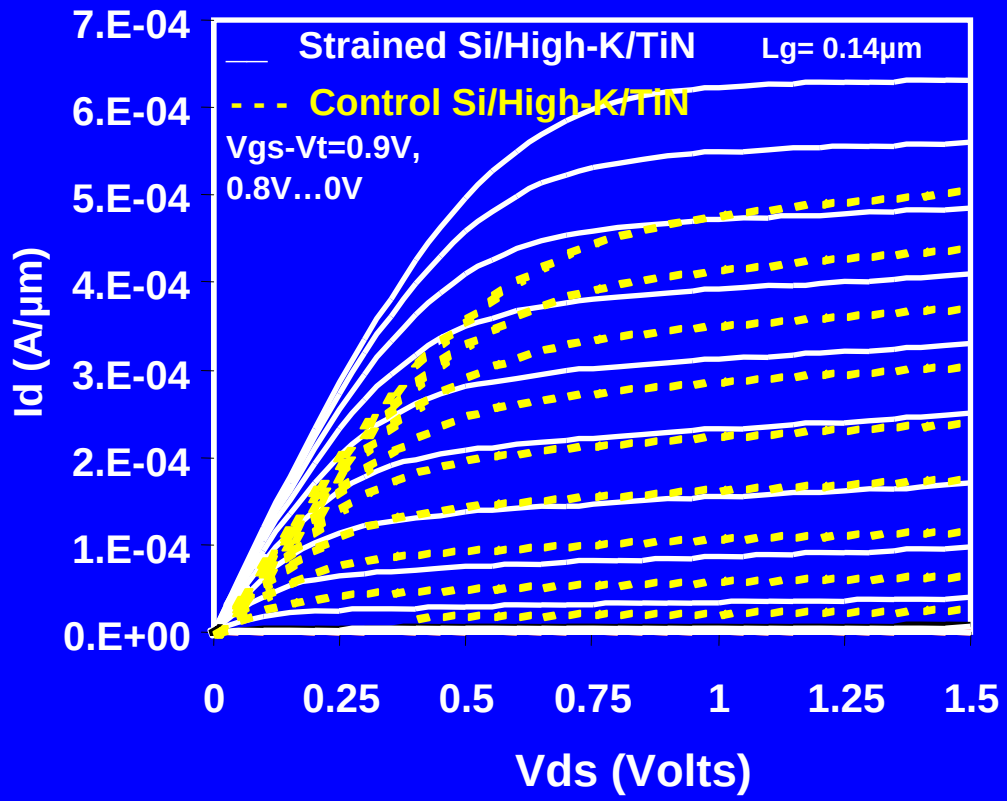
- Electron mobility improves due to strain from i) transport mass improvement from repopulation and ii) reduction in inter-valley scattering

Further Mobility Enhancement with Mid-Gap TiN + Strained Si



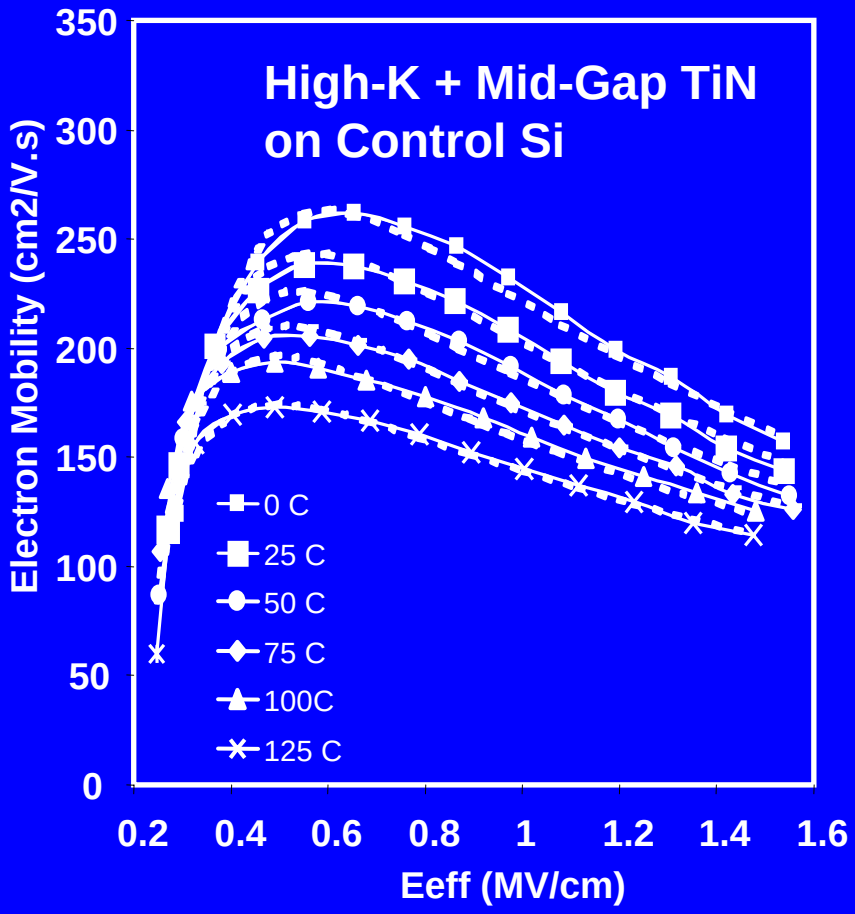
- Electron mobility is enhanced above the SiO2 universal mobility curve with the addition of strained Si

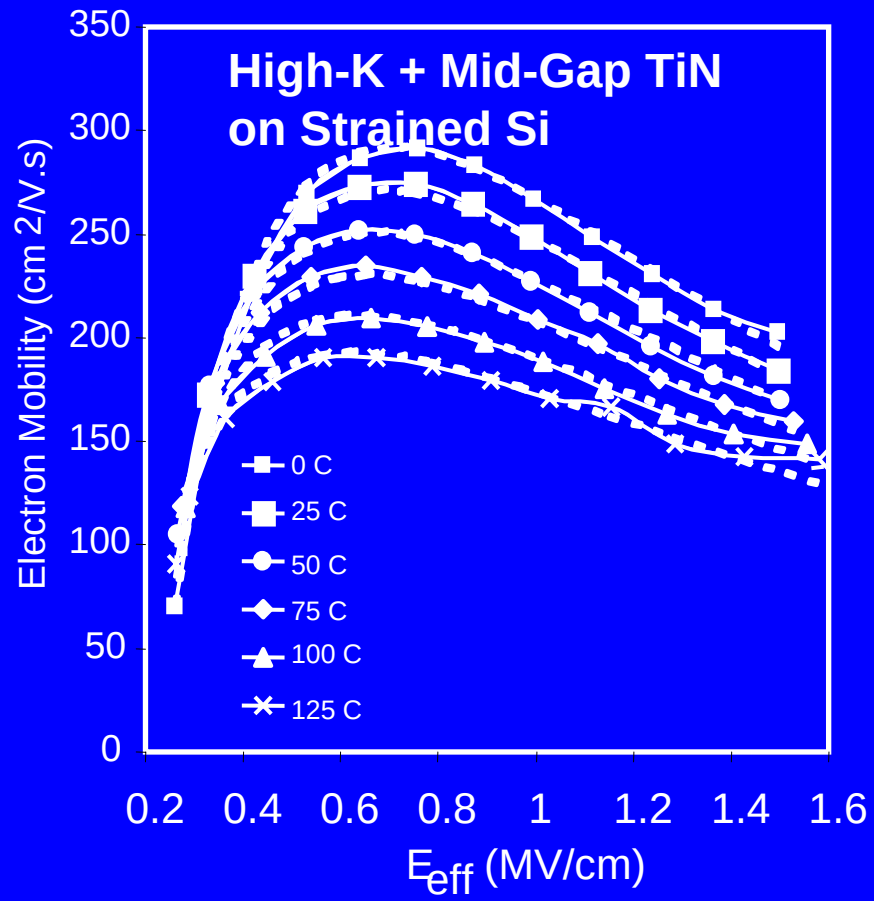
Performance Improvement from Strained Si



- Strain results in 24% improvement in Idsat and 43% improvement in Idlin

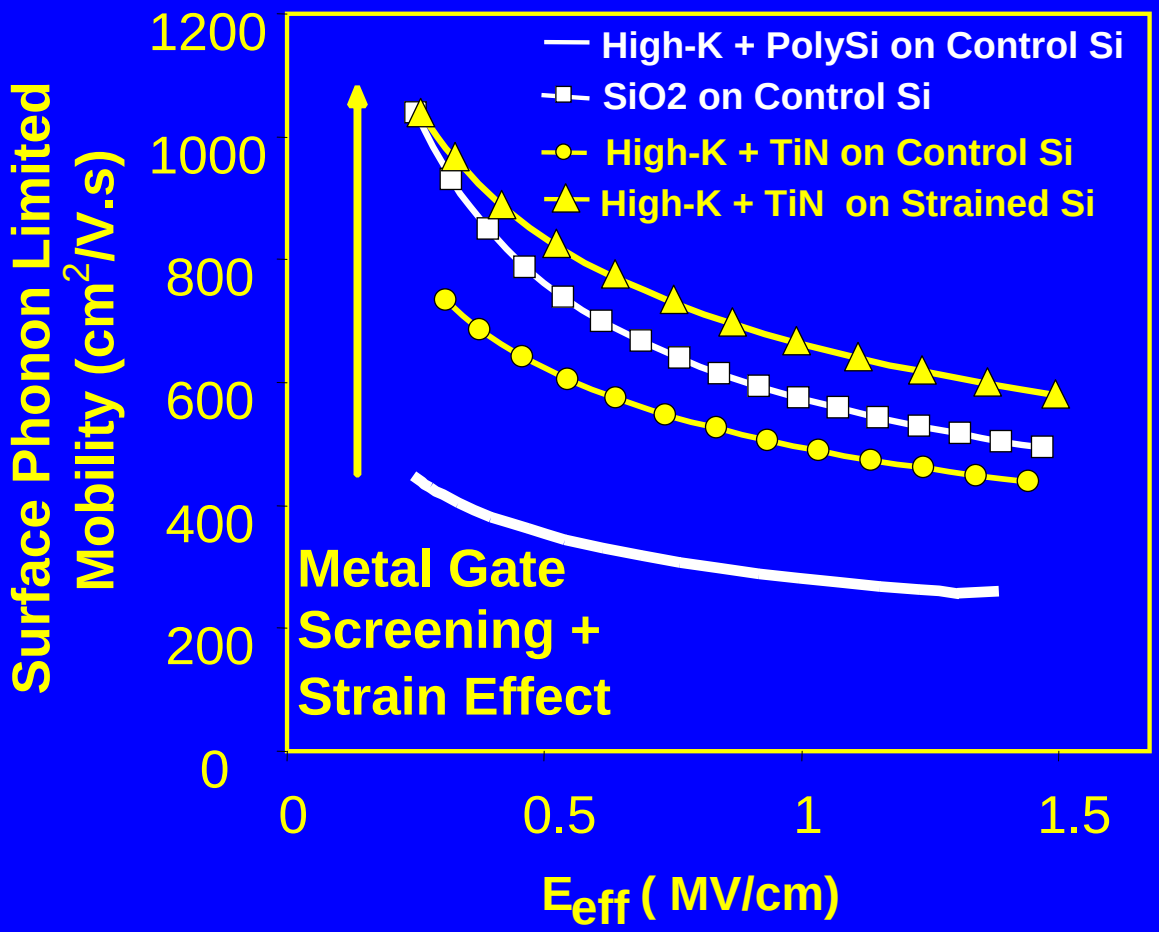
Mobility – Temp Behavior





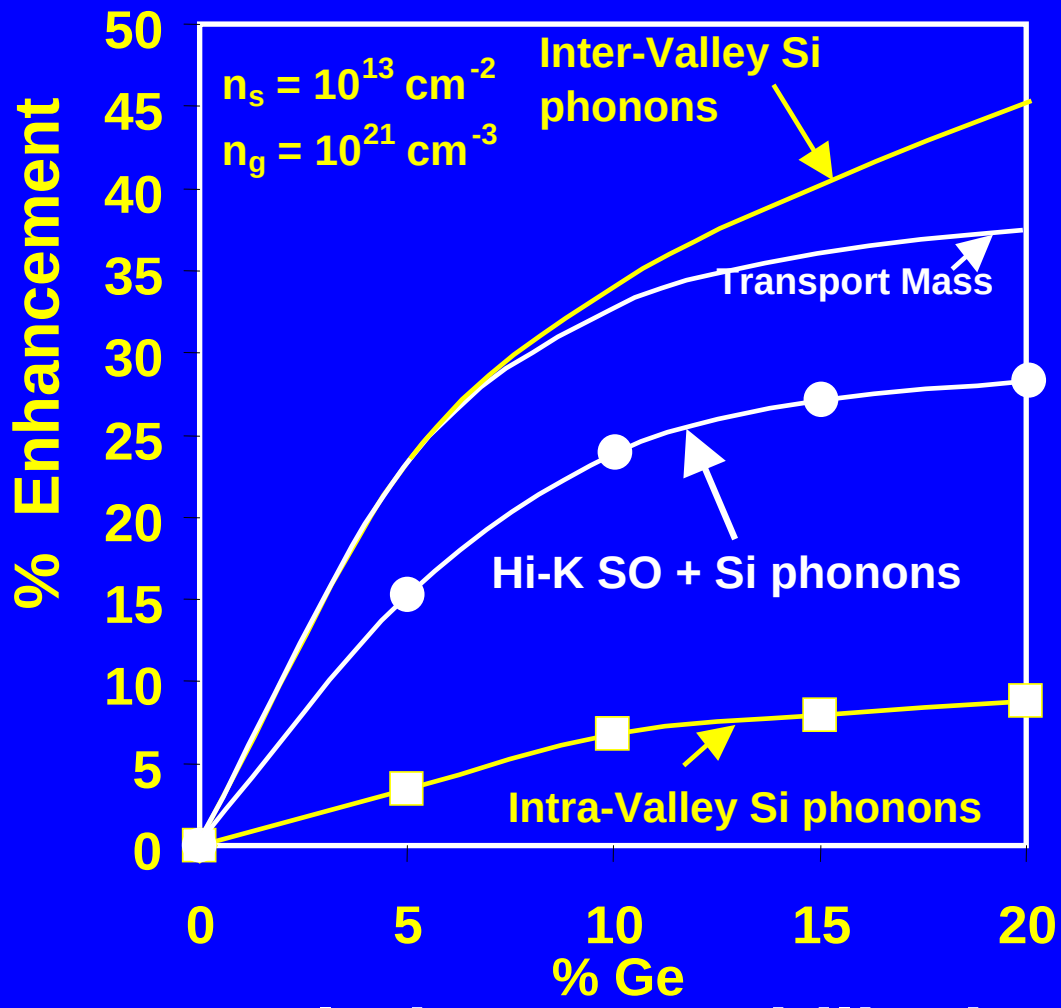
- **Temperature sensitivity study enables extraction of the individual mobility components**

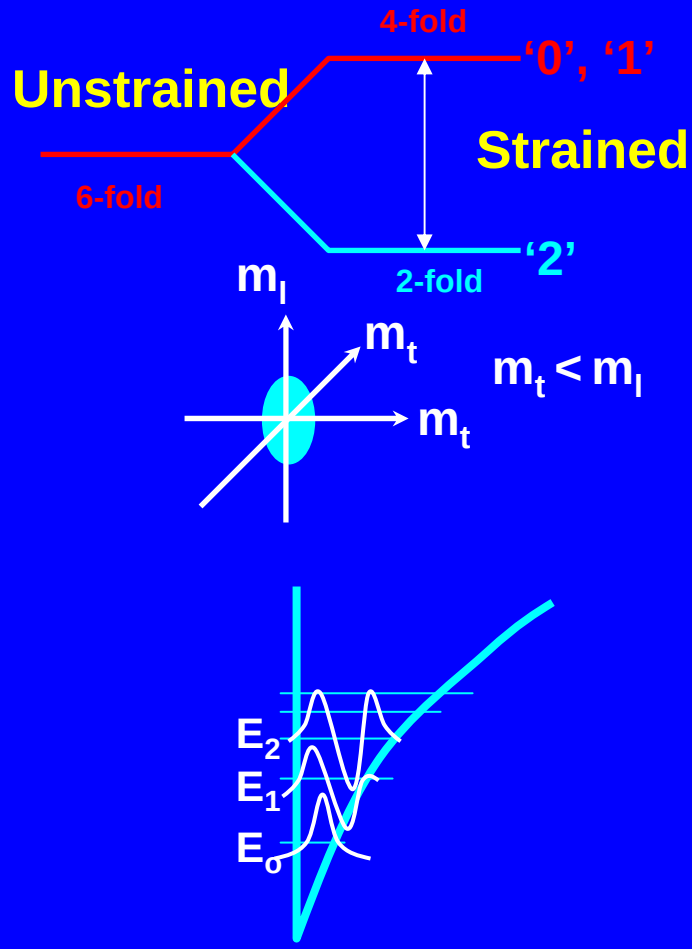
Surface Phonon Mobility



- **Phonon Mobility improves significantly with Mid-Gap TiN metal gate and strained Si**

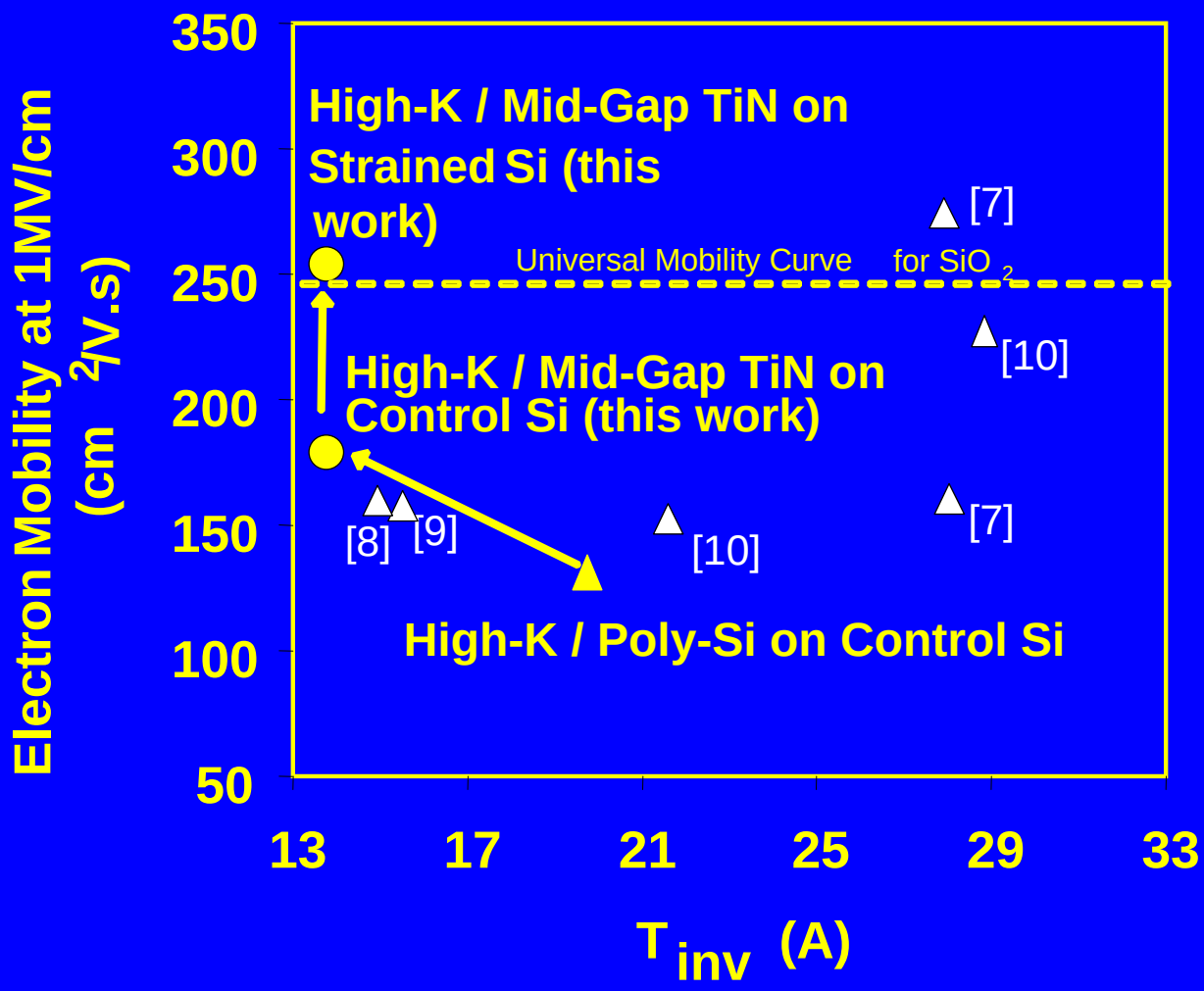
Physics-based Simulation





- **Total Phonon mobility including SO phonons improves with strain**

Mobility – Tox (inv)

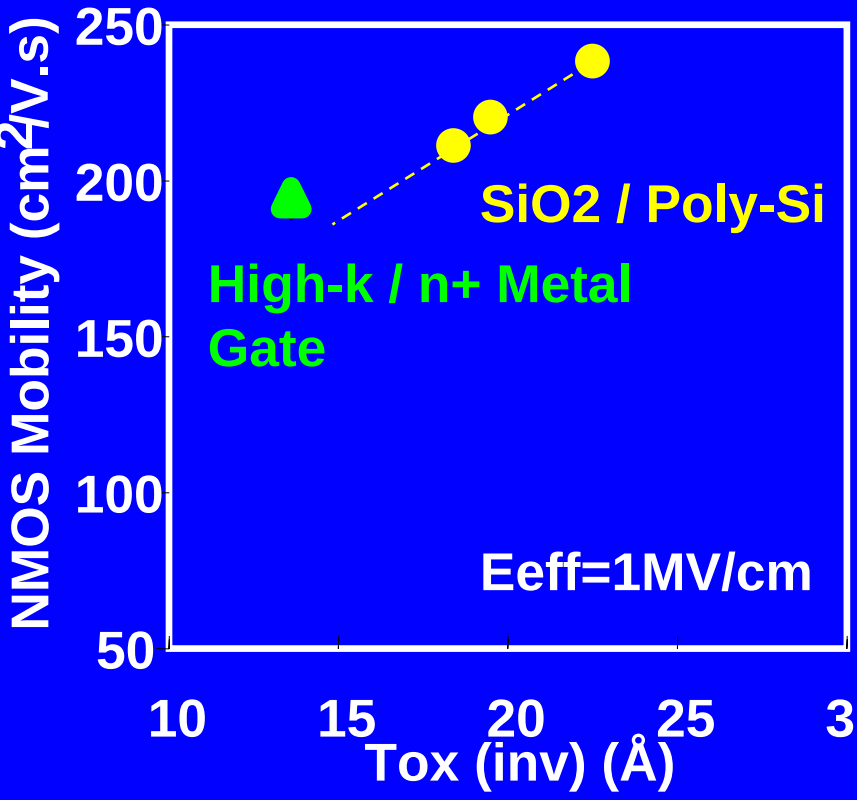


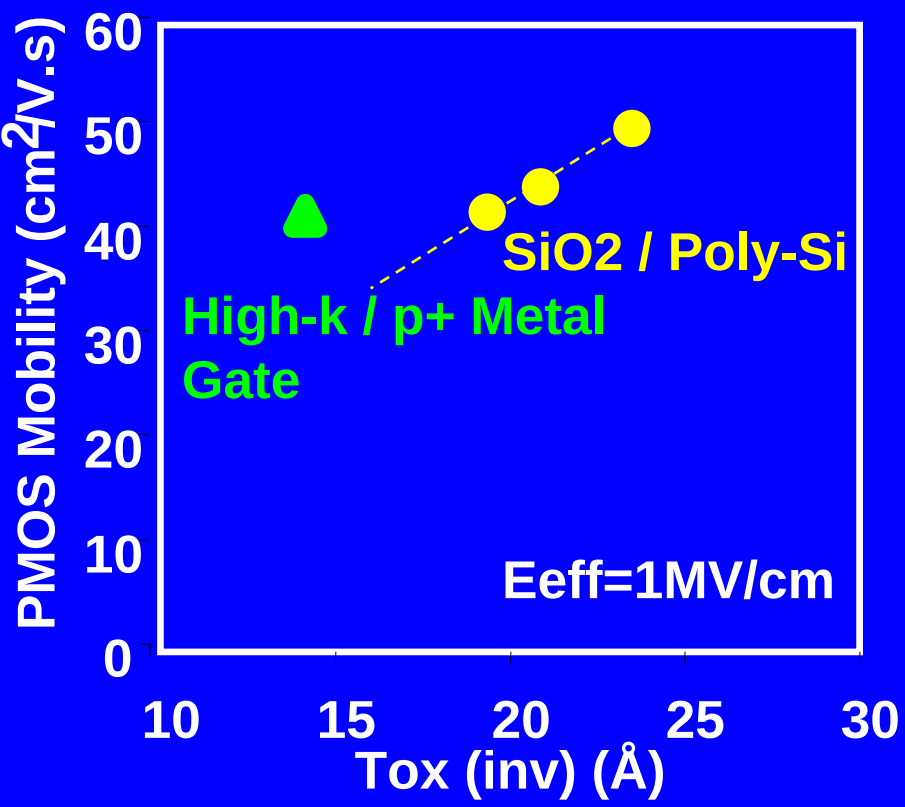
- **Highest transconductance achieved by combining High-K / Mid-Gap TiN Metal Gate with Strained Si channel**

From Mid-Gap TiN to n+ and p+ Work-Function Metals

- Mid-Gap TiN electrode screens the high-K SO phonons from coupling to the inversion channel charge carriers and improves the High-K mobility
- Mid-Gap TiN electrode results in high Vt for both NMOS and PMOS causing poor drive performance
- For high performance CMOS, the use of High-K/metal-gate requires metal gate electrodes with the “correct” n+ and p+ work functions on High-K
- Do n+ and p+ Work-Function Metal Gate Electrodes effectively screen High-K SO phonons, and improve High-K mobility ?

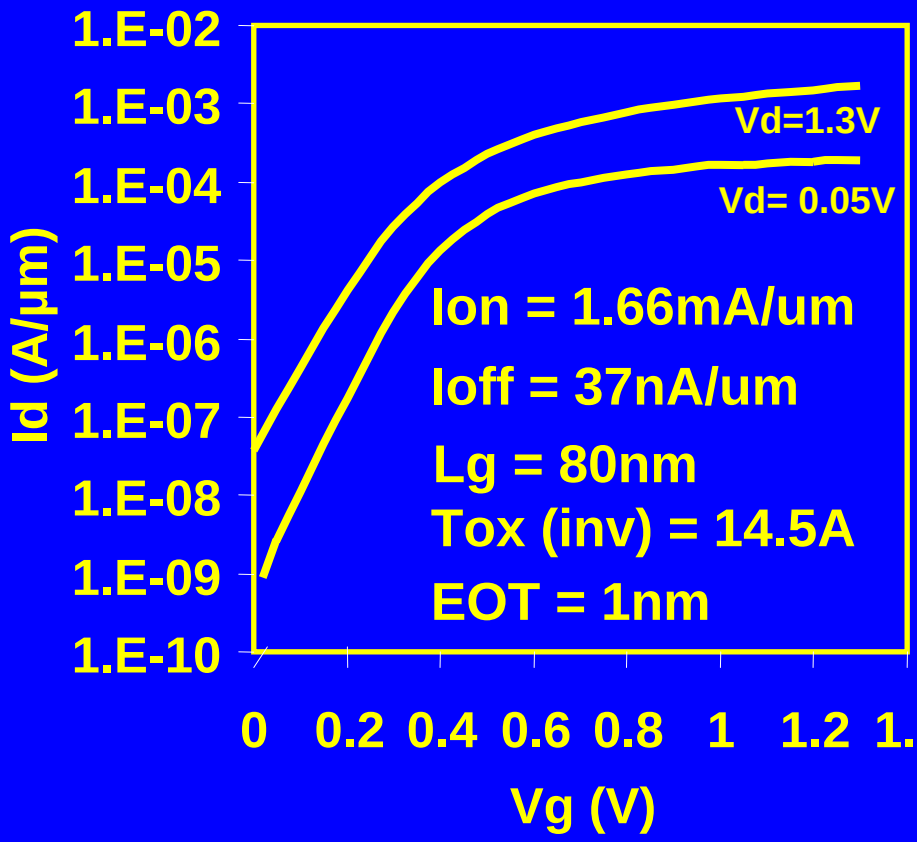
n+ and p+ High-K/Metal-Gate Stack Achieves Mobility Close to SiO2 for both NMOS and PMOS

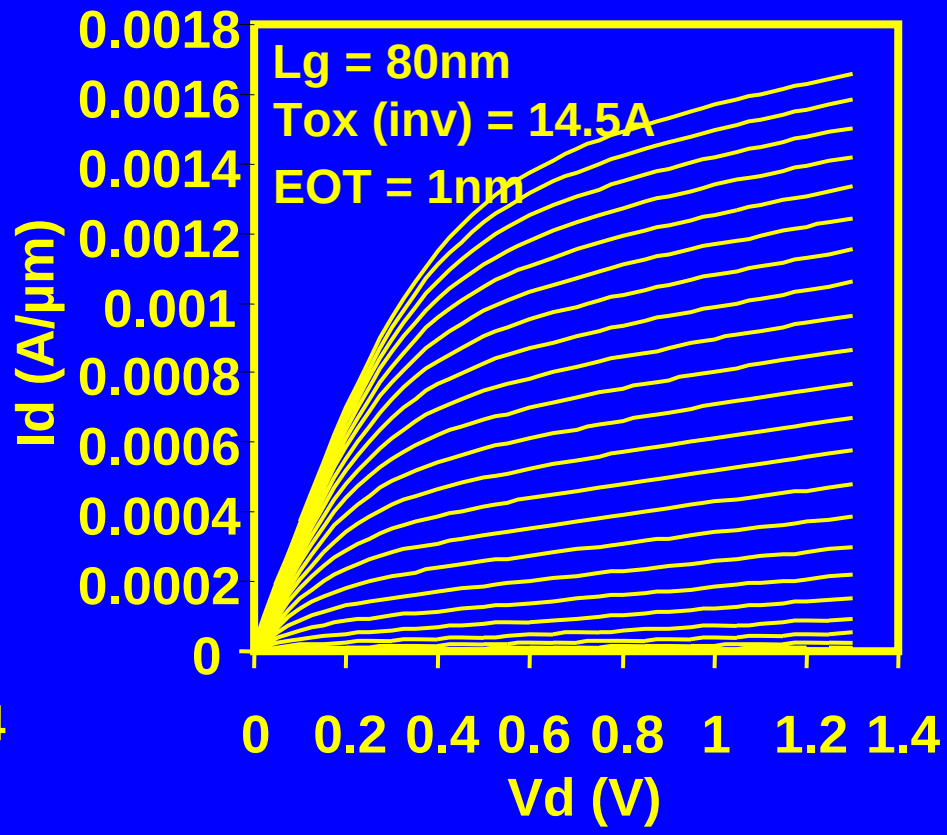




- *R. Chau et al.* , International WorkShop on Gate Insulator, Tokyo, Nov 06 2003

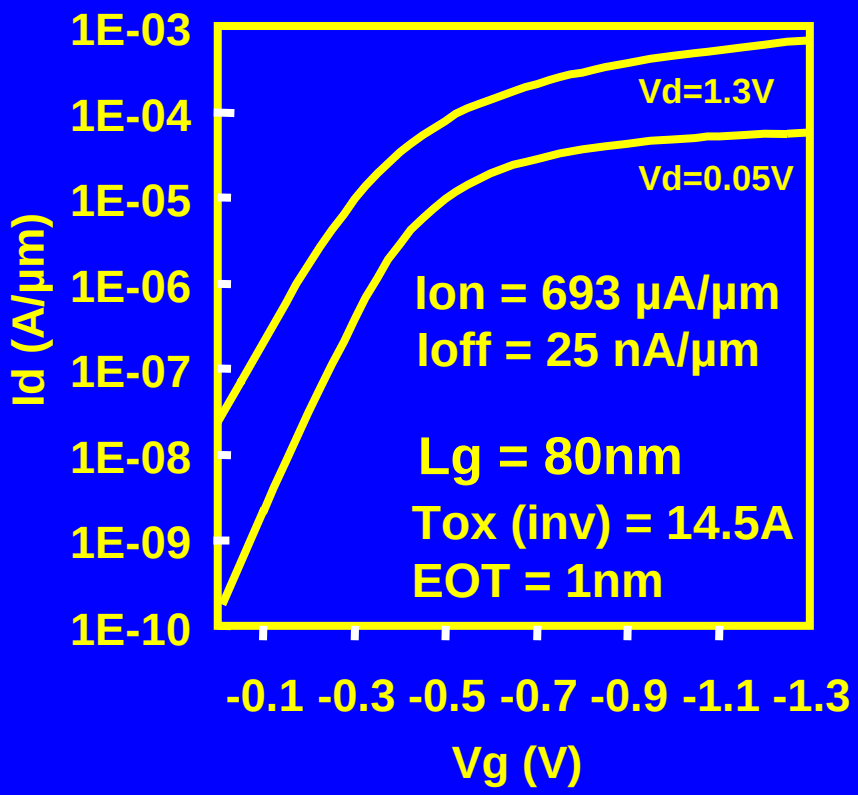
High-K / n+ Work-Function Metal-Gate NMOS achieves expected Drive Current Performance

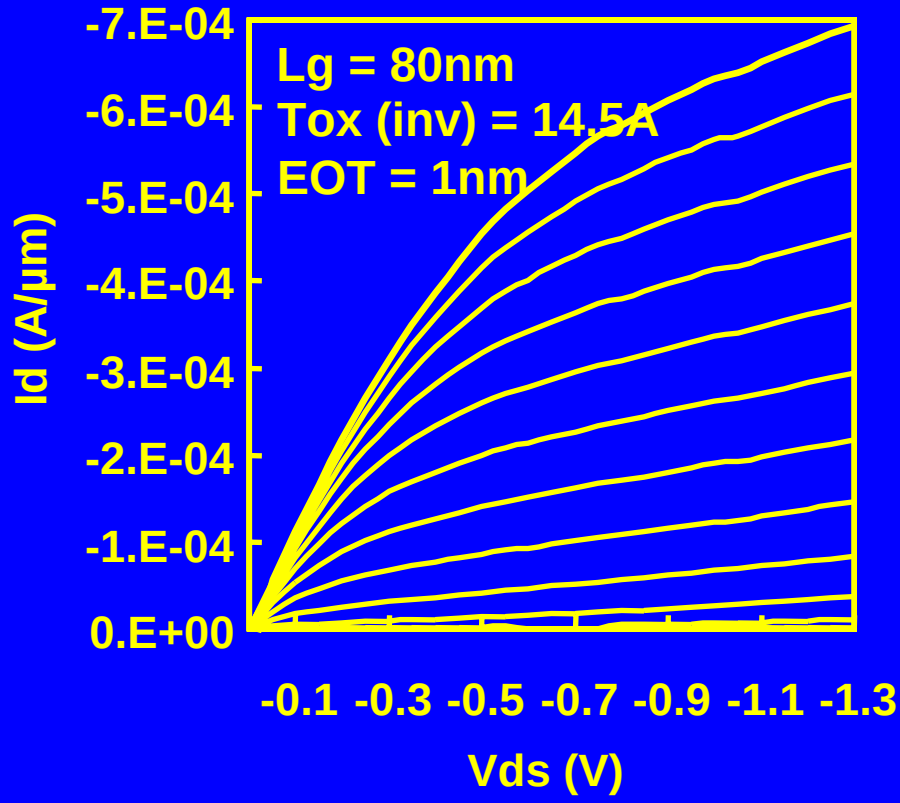




- R. Chau et al. , “Gate Dielectric Scaling for High-Performance CMOS: from SiO2 to High-K,” Extended Abstracts of International Workshop on Gate Insulator 2003, Tokyo, Japan, Nov. 2003, p.124-126

High-K / p+ Work-Function Metal-Gate PMOS achieves expected Drive Current Performance





- R. Chau et al. , “Gate Dielectric Scaling for High-Performance CMOS: from SiO2 to High-K,” Extended Abstracts of International Workshop on Gate Insulator 2003, Tokyo, Japan, Nov. 2003, p.124-126

Conclusions

- SO phonon induced scattering is the primary cause of electron mobility degradation in High-K gate dielectric
- High-K / TiN Mid-Gap Metal Gate stack can be combined with strained Si channel to achieve electron mobility better than the SiO2 universal mobility curve
- n+ and p+ work-function Metals can also effectively screen the High-K SO phonons and improves mobility
- **Next Step:** Combine n+ and p+ work-function Metal Gate Electrodes with High-K and Strained Si